

*Hill* *SM*  
*graf*

National Aeronautics and Space Administration  
Goddard Space Flight Center  
Contract No. NAS-5-3760

ST - RWP - AI - 10354

COMPUTATION OF THE ABSORPTION FACTOR OF CENTIMETER AND  
MICROWAVES IN THE ATMOSPHERE OXYGEN

by

S. A. Zhevakin  
A. P. Naumov

(U S S R)

FACILITY FORM 602

N66-86481	(THRU)
(ACCESSION NUMBER)	<i>none</i>
16	(CODE)
(PAGES)	
CP 77715	(CATEGORY)
(NASA CR OR TMX OR AD NUMBER)	

9 JULY 1965

COMPUTATION OF THE ABSORPTION FACTOR OF CENTIMETER AND  
MICROWAVES IN THE ATMOSPHERE OXYGEN \*

Radiotekhnika i Elektronika  
Tom 10, No. 6, 987 - 996  
Izdatel'stvo "NAUKA", 1965

by S. A. Zhevakin,  
A. P. Naumov

SUMMARY

This paper is a critical review of calculations of absorption factors in the atmosphere oxygen of radiowaves in centimeter and microwave bands. The absorption factor of  $O_2$  at sea level is calculated in  $\lambda \approx 2.2 \text{ mm} - 10 \text{ cm}$  wavelength with the shape of the line obtained from the solution of the kinetic equation. From the comparison of the computed absorption factor with the experimental one in the  $\lambda \approx 4.3 - 6.7 \text{ mm}$  wavelength region the mean value has been found of the half-width of the spectral line  $\Delta\nu_{K\pm} = 0.81 \text{ G cps at } P = 760 \text{ mm Hg.}$ \* For a polytropic model of the atmosphere the equivalent path length  $H$  of radiowaves in oxygen beyond resonance was obtained equal to  $5.1 - 5.3 \text{ km}$ . In the resonance region  $\lambda \approx 5 \text{ mm}$ , the quantity  $H$  can acquire values  $\sim 8 - 21 \text{ km}$ .

\* \* \*

The weakening of centimeter and microwaves in the atmosphere is to a significant degree determined by absorption of oxygen and water vapor molecules. The absorption factor of water vapor was computed by us in the works [1 - 3]. In the present paper we shall discuss the methods of computation of  $O_2$  absorption factor.

The first calculations of oxygen absorption factor were completed by Van Vleck [4] in 1947. During the time elapsed since then the Van Vleck theory underwent no principle variations of any sort, although the

---

\* K RASCHETU KOEFFITSIENTA POGLOSHCHENIYA SANTIMETROVYKH I MILLIMETROVYKH RADIOVOLN V ATMOSFERNOM KISLORODE

\*\*[G will be used sometimes to denote "giga" or  $10^9$ ]

results of [4] were more than once polished up and made more precise [5 — 8]. The opinion existed [9 — 12] that the computed absorption factor for  $O_2$  is in good agreement with the experiment and does not reveal "anomalies", inherent for example to the absorption factor of water vapor (this, incidently, is dealt with at further length in [3]). However, the development of measurement methods and techniques allowed to be more specific about the presence of a discrepancy between experiment and theory in regard to this question. The recent measurements of oxygen absorption in decimeter waves [13] provided in particular significant excesses over the computed absorption factor. In connection with this there are in [13, 14] critical remarks in regard to the computation of nonresonance absorption in the Van Vleck theory\*. Quite contradictory data on the half-widths of  $O_2$  spectral lines are brought up in literature (see [5, 9, 12, 16 — 26]) and the same can be said of the equivalent path length of radiowaves in oxygen [11, 27 — 32]. We shall pause only at separate questions of oxygen absorption spectrum description, currently under discussion. Details on  $O_2$  molecule and its spin-rotational spectrum can be borrowed from [4, 32 — 35]. We shall denote in the following by  $K_-$  the transitions  $J + 1 \rightarrow J$  and the transitions  $J + 1 \rightarrow J -$  by  $K_+$ ; the respective resonance frequencies will be denoted by  $\nu_{K_-}$  and  $\nu_{K_+}$  and the half-widths — by  $\Delta\nu_{K_-}$  and  $\Delta\nu_{K_+}$  ( $K$  being the quantum number of the azimuthal moment of nucleus' quantity of motion,  $J$  is the quantum number of the total moment of the quantity of motion of the molecule).

1. Amongst peculiarities of the considered absorption spectrum of  $O_2$  is the comparatively small scattering of resonance frequencies  $\nu_{K\pm}$ , lying in a narrow band  $\delta\nu \simeq 10$  cps, centered near  $\nu = 60$  cps\*\*.

---

\* The experimental results of [15] exceeded the computed by nearly a factor of 2 [4] at  $\lambda = 20$  cm. However, the work [15] is not free from shortcomings in regard to measurement method.

\*\* We have in mind all the transitions to  $K = 49$  except  $1_-$ . The transitions with  $K > 29$  did not contribute notably to absorption because of low population of the levels at heights  $z < 20$  km, where the spectral lines of  $O_2$  already allowed. At heights  $z \simeq 30$  km the absorption factor of atmosphere oxygen exceeds the corresponding values in the minima by a factor of 2 and more even in peaks of weak lines with  $K \simeq 45$ . It is author's [36] opinion

and the presence of nonresonance absorption\*. The first circumstance is conditioning the overlapping of spectral lines at pressures  $P \gtrsim 30$  mm Hg., and it explains the fact that the linear extrapolation  $\Delta\nu_{K\pm} \sim P$  of lines' half-widths, measured at low pressure ( $P \simeq 2 - 10$  mm Hg), leads to over-rated values of  $\Delta\nu_{K\pm}$  at  $P = 1$  atm by comparison with the estimates of  $\Delta\nu_{K\pm}$  by the magnitude of the measured absorption at  $P = 1$  atm.\*\*. In order to coordinate the contradictory data on the half widths of spectral lines [5, 9, 12, 16 - 26], an assumption is made in a series of latest works [8, 12, 38] on the nonlinear dependence of  $\Delta\nu_{K\pm}$  on  $P$ . At present, there is still no question of speaking in terms of exact description of this dependence, but its rough approximations were already utilized in the computations of [8, 12]. Note, however, that in the work [8] all the nonlinearity amounts to dependence on pressure ratio  $\beta(P) = \sigma_{O_2-N_2}/\sigma_{O_2-O_2}$  ( $\sigma$  being the collision cross section). Meanwhile, there is no basis for such an assumption within the framework of the theory of binary collisions, according to which  $\beta$  should not be dependent on pressure. Fulfillment of the correlation  $\Delta\nu_{K\pm} \sim P$  ought to be expected in the pure oxygen if assumptions of [8] are retained, for all  $P$ , at which triple collisions could be neglected, although spectral line overlapping takes place even in that case.\*\*\*

---

[continued from \* preceding page] ... that temperature fluctuations at heights  $z \gtrsim 30$  km may change the population levels of  $O_2$  molecules, that even weak lines, such as, for example,  $\nu_{27-}$  become observable in the telluric spectrum of the Sun.

\* We make use of the generally accepted terminology "nonresonance absorption" though from the physical essence this term is not accurate (see [14]).

\*\* According to measurements of [19, 21] and also to computations after the Anderson theory [21], the mean value of the ratio  $\Delta\nu_{K\pm}/P$  in pure oxygen is  $(\Delta\nu_{K\pm}/P)_{\text{aver}} = 1.95$  mc/mm Hg; hence, taking into account the small difference of the effective cross section of collisions  $O_2 - N_2$  from that of  $O_2 - O_2$  (according to a series of measurements [21, 37] their ratio is  $\beta \simeq 0.90$ ), and the correlation  $\Delta\nu_{K\pm} \sim P$ , we obtain at  $P = 1$  atm in the air  $\Delta\nu_{K\pm} \simeq 1.35 \cdot 10^9$  cps ( $0.045$  cm $^{-1}$ ), that is by a factor of  $\sim 2$  greater than would follow from measurements of [5, 9, 12, 16].

\*\*\* Qualitatively, the nonlinear dependence  $\Delta\nu_{K\pm}(p)$  can be explained, by considering interaction of two standard models of absorbing molecules — harmonic oscillators.

All the available data on oxygen absorption in the atmosphere (see below), as well as in its pure state (see [39]), can be interpreted by estimating the factor  $\alpha_{K\pm}$  in the expression

$$\Delta\nu_{K\pm} = \alpha_{K\pm} P (0,21 + 0,78\beta) (T/300)^{-n_{K\pm}} \quad (1)$$

from the work [2], as being dependent on P.

The following empirical formula is proposed in the work [12] for the description of the dependence  $\Delta\nu_{K\pm}(P)$ , obtained from observations of oxygen absorption in the region  $\nu = 58 - 62$  cps at several pressures:

$$\Delta\nu_{K\pm} = 1,9 \cdot 10^{-3} P \left( \frac{760}{760 + P} \right) \left( \frac{290}{T} \right)^{0,9} \quad (2)$$

We shall pause below at the results of calculation of the values of  $\Delta\nu_{K\pm}$  by formulas (1) and (2). We should note here only, that the comparison of the measured and computed absorption factors of  $O_2$  in the region  $\nu = 58 - 62$  cps only, cannot allow to determine somewhat reliably the form of the function  $\Delta\nu_{K\pm}(P)$  outside the interval  $\nu = 58 - 62$  G. cps.

It may be seen from Fig. 1 [next page] and Fig. 6 of the work [12], that at the very least the band  $\nu = 50 - 70$  cps should be utilized for that purpose at various pressures.

As to the nonresonance absorption of oxygen, it is described, to the best of our knowledge, by a Debye-type expression in all foreign publications available to us. This expression was obtained in the limit case, at oscillator natural frequency approaching zero, by Van-Vleck-Weisskopf [40]. A thorough criticism of initial postulates and results of the said authors was given in [41], and more particularly in [42]. Here it should be stressed once more, that the limit expression, obtained in [40], has no relation to nonresonance absorption of oxygen, for in [40] the ultimate transition has been materialized to the case of a free electron, whereas the nonresonance absorption of  $O_2$  has an entirely different nature [14, 39]. The fact that for describing nonresonance absorption an incorrect expression was used for 20 years is apparently also explained by the Van Vleck-Weisskopf limit expression, inherently wrong, having led, at selection of the magnitude of the parameter  $\Delta\nu_0$ , to a valid order of nonresonance absorption at sea level in the  $\lambda \simeq 3 - 10$  cm band.

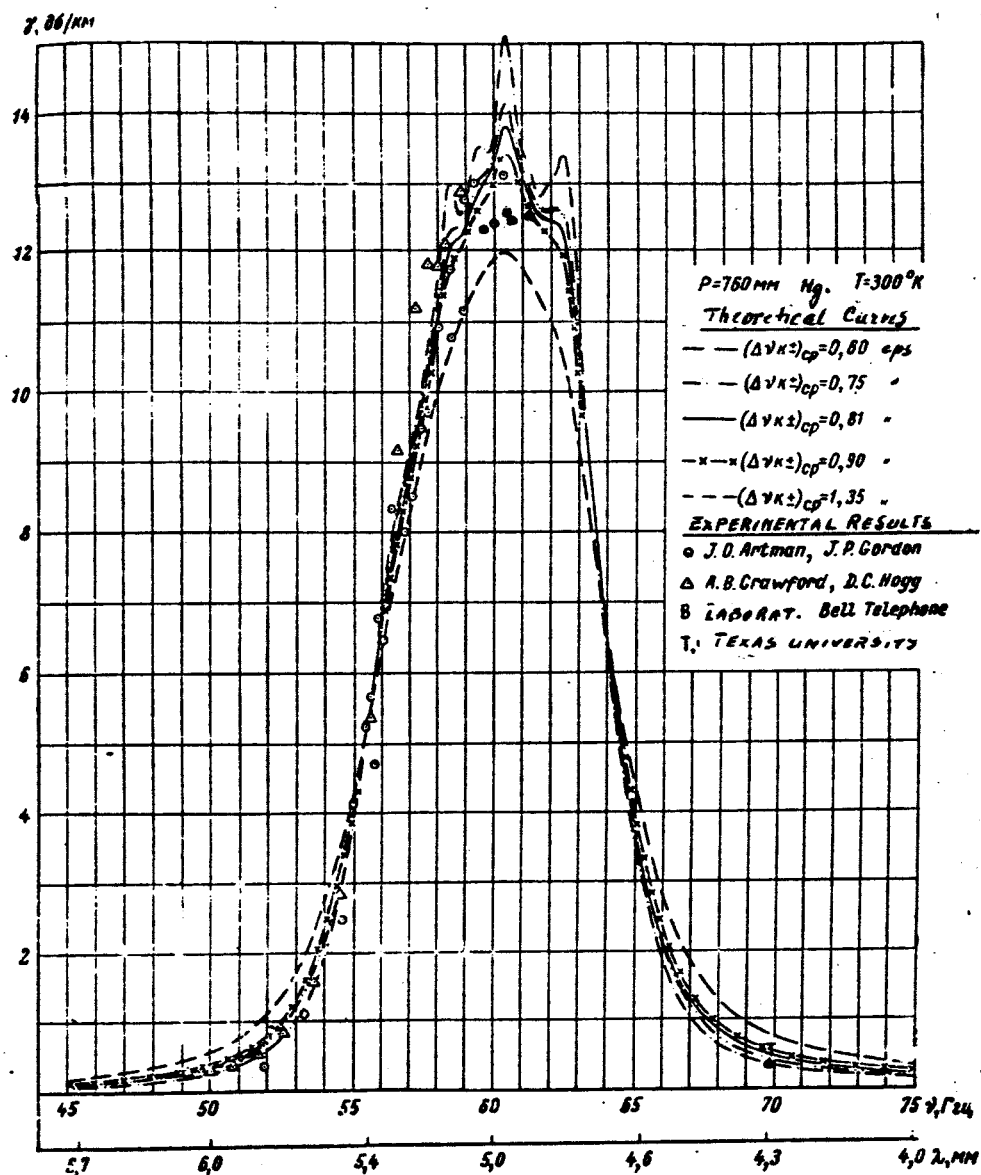


Fig. 1. Comparison of the experimental results of [5, 21, 22, 50] with the absorption factors computed with line shape according to the kinetic equation at various values of  $(\alpha_{K\pm})_{\text{aver.}}$  within the  $\lambda \approx 4.3 - 6.7 \text{ mm}$  band. The experimental points are situated either at the center or at intersections of the respective signs.

In [14] an approximate expression was obtained for the nonresonance absorption of oxygen at specific idealizations, making use of the density matrix. Empirical correlations are sometimes used for estimates of nonresonance parts of absorption (see, for example, [39]).

The resonance part of oxygen absorption is described in the present work by the usual method: the molecule is modeled by linear harmonic oscillator with a natural frequency  $\nu_{K\pm}$  and situated in an external electromagnetic field, undergoing collisions with other molecules. However, assuming that an erroneous shape of the Van-Vleck-Weisskopf line was utilized in all the preceding computations of the microwave spectrum of oxygen, below, the following expression for the spectral line is that obtained from the solution of the kinetic equation:

$$f(\nu, \nu_{K\pm}) = \frac{\nu^2}{\pi} \frac{4\Delta\nu_{K\pm}}{(\nu_{K\pm}^2 - \nu^2)^2 + 4\nu^2(\Delta\nu_{K\pm})^2} \quad (3)$$

The deriving of the expression (3) is free from shortcomings of principle, though it was made in certain idealizations (see for details [1, 42]). The Earth's magnetic field (Zeeman effect) and the Doppler shift do not exert any effect on the shape of the absorption line of  $O_2$  at heights  $z < 40$  km [43, 44]. An attempt has been made in [37] to determine experimentally the shape of the absorption line of oxygen. However, the latter measurements were made near the resonance, where all the currently known spectral lines are close to one another. That is why, no choice of any shape can be made amongst absorption lines, based upon the results of the work [37].

2. We made the computation of the absorption factor of oxygen using the formula

$$\gamma[\partial\delta/\kappa M] = A_1 P T^{-3} \sum_K (F_{K+} \mu_{K+}^2 + F_{K-} \mu_{K-}^2 + F_0 \mu^2) A_K, \quad (4)$$

where  $A_1 = 2.6742$ ;  $P$  and  $T$  are the pressure (in mm.Hg) and the absolute temperature;  $\nu$  is the frequency of the external field in giga-cps;  $A_K = \exp(-BhcK(K+1)/KT)$ ; the rotational constant of the oxygen molecule  $B = 1.44 \text{ cm}^{-1}$ ;  $h$ ,  $c$ ,  $k$  are the Plank constant, the speed of light and the Boltzmann constant, respectively;

$$\mu_{K+}^2 = K(2K+3)/(K+1); \mu_{K-}^2 = (K+1)(2K-1)/K;$$

$$\mu_0^2 = 2(K^2 + K + 1)(2K+1)/K(K+1);$$

for the line shape obtained from the solution of the kinetic equation

$$F_{K\pm} = 4\nu_{K\pm}^2 \Delta\nu_{K\pm} / [(\nu_{K\pm}^2 - \nu^2)^2 + 4\nu^2(\Delta\nu_{K\pm})^2].$$

In the nonresonance term of (4)

$$\gamma_{nr} = A_1 P T^{-3} \nu^2 \sum_K F_0 \mu_K^2 A_K$$

it was postulated

$$\bar{F}_0 = \Delta\nu_0 / (\nu^2 + \Delta\nu_0^2) \text{ c } \Delta\nu_0 = 0.6 \text{ cps};$$

at such assortment of the value of  $\Delta\nu_0$  the nonresonance term describes not too badly the absorption in the 8–30 mm band, though, as already noted above, such description methods induce objections of principle\*. In the calculation resonance frequencies  $\nu_{K\pm}$ , borrowed from [45] (see also the Table 1 from [39]), were utilized. At  $K \leq 23$ , the frequencies referred to were computed in [25, 46] and are found in good agreement with the measurements of [18, 20, 25, 46], the discrepancies not exceeding 0.003%. The circumstance noted permits to hope for a high degree of precision of frequencies  $\nu_{K\pm}$ , computed at  $25 \leq K \leq 49$ , which were not measured. A hypothesis is made and "substantiated" in a series of foreign publications [47–49] about a decrease of resonance frequencies of  $O_2$  with pressure increase in pure oxygen. But the shift of resonance frequencies of  $O_2$  must also be noticeable in the atmosphere oxygen, provided it occurs at oxygen concentration to 100%, for the short-range molecular interactions (London dispersion, exchange forces), being nearly identical in both cases, lead to effective collision cross sections close to one another ( $\beta \simeq 0.90$ ) [21, 37]. However, it is shown in [39], that there is in fact no basis to estimate the frequencies  $\nu_{K\pm}$  as dependent on pressure  $P$ , at least to  $P \simeq 7-8$  atm.

The quantity  $\Delta\nu_{K\pm}$  was computed according to (1), the value of  $\beta$  being assumed equal to 0.90 [21, 37]; the temperature factor  $\alpha_{K\pm}$  was taken equal to 0.85 for all transitions, as the average result of measurement for five spectral lines of  $O_2$  [24], and the mean value of  $(\alpha_{K\pm})_{\text{aver.}}$  was picked up from the comparison of the computed absorption factor with the experimental one in the region  $\lambda \simeq 4.3-6.7$  mm (under normal conditions the nonresonance absorption in this band is neglectingly small).

---

\* In wavelengths  $1 \text{ cm} \leq \lambda \leq 3 \text{ cm}$ , the nonresonance absorption  $\gamma_{nr}$ , computed as indicated, constitutes no less than 35% of the total absorption  $\gamma$  in oxygen, and in the band  $\lambda > 3 \text{ cm}$ , it defines fully the absorption factor of  $O_2$ . In the region of minimum oxygen absorption  $\gamma \simeq 3 \text{ mm}$  (see Fig. 2) the ratio  $\gamma_{nr}/\gamma \simeq 0.02$ , in wavelengths  $\lambda \leq 2.4 \text{ mm}$  it is  $> 0.4$ . In the peaks of absorption ( $\lambda \simeq 5 \text{ mm}$ ) and  $\simeq 2.5 \text{ mm}$ ) we have respectively. (see next page)



By the method of least squares we found the optimum value of  $(\alpha_{K\pm})_{av}$  as being equal to 1.17 mc/mmHg at  $P = 760$  mm Hg, which corresponds to  $(\Delta\nu_{K\pm})_{av} = 0.81$  giga-cps  $= 0.027$   $\text{cm}^{-1}$  (see Fig. 1). For the line 1. it was assumed  $\alpha_1 = 2.064$  mc/mm Hg [21] (the nearest lines are remote from  $\lambda_1 \approx 2.53$  mm), which corresponds under normal conditions to  $\Delta\nu_1 = 1.43$  cps. The last result coincides with the value measured in [23]. From formula (2) in the region  $\lambda \approx 5$  mm at  $P = 760$  mm Hg and  $T = 300^\circ$  K it follows that  $\Delta\nu = 0.70$  giga cps  $= 0.023$   $\text{cm}^{-1}$ . But the authors of [12] utilized in the calculation of the absorption factor of  $O_2$  the Van Vleck-Weisskopf formula which, as already noted above, leads to a somewhat different value of  $(\alpha_{K\pm})_{av}$  than the line shape from the kinetic equation, though in resonance both formulas differ little from one another \*\*. The optimum value of  $(\alpha_{K\pm})_{av}$  found by us for the shape of the Van Vleck-Weisskopf line at  $P = 760$  mm Hg and  $T = 300^\circ$  K, gives  $(\Delta\nu_{K\pm})_{av} = 0.032$   $\text{cm}^{-1}$ . Such discrepancy in the results for one and the same shape of the line (0.023 and 0.032  $\text{cm}^{-1}$ ) should be entirely ascribed to the degree of carefulness in the determination of the corresponding parameters. Let us stress once more that at finding the optimum value of  $(\alpha_{K\pm})_{av}$  we made use of the method of least squares and we took into account the experimental data in the region  $\nu \approx 50 - 70$  cps.

It was unanimously estimated that the quantity  $(\Delta\nu_{K\pm})_{av}$  did not exceed 0.02  $\text{cm}^{-1}$  under standard conditions. Tolbert & Straiton [9], whose experimental data contributed to a significant extent to the verification of the theory of molecular absorption of  $O_2$ , held down also to that opinion. However, as the experimental material accumulated, it became possible to make the value of  $(\Delta\nu_{K\pm})_{av}$  more precise. It is now estimated, that at standard conditions  $(\Delta\nu_{K\pm})_{av} > 0.02$   $\text{cm}^{-1}$  [5, 12]. But, careful comparison of the measured absorption factor of  $O_2$  with that computed according to the kinetic equation - given line shape, gives, as already seen, the value  $(\Delta\nu_{K\pm})_{av} = 0.027$   $\text{cm}^{-1}$ .

We considered above only the main isotope of the oxygen molecule,  $O^{16}O^{16}$ . Since the percent content of isotopes  $O^{16}O^{17}$ ,  $O^{16}O^{18}$  and  $O^{18}O^{18}$  in the atmosphere is less than one perc. of the total oxygen content [51] and their resonance frequencies differ insignificantly from the resonance frequencies of  $O^{16}O^{16}$  [52, 53], we may neglect the influence of oxygen

(continued from p. 7) ..  $\gamma_{nr}/\gamma \approx 0.0007$  &  $\gamma_{nr}/\gamma \approx 0.007$ . The figures brought up allow a qualitative appraisal of the inaccuracy in the range of the computed factor because of incorrect accounting of nonresonance absorption.

isotopes upon the absorption factor of centimeter and millimeter radio-waves without noticeable error.

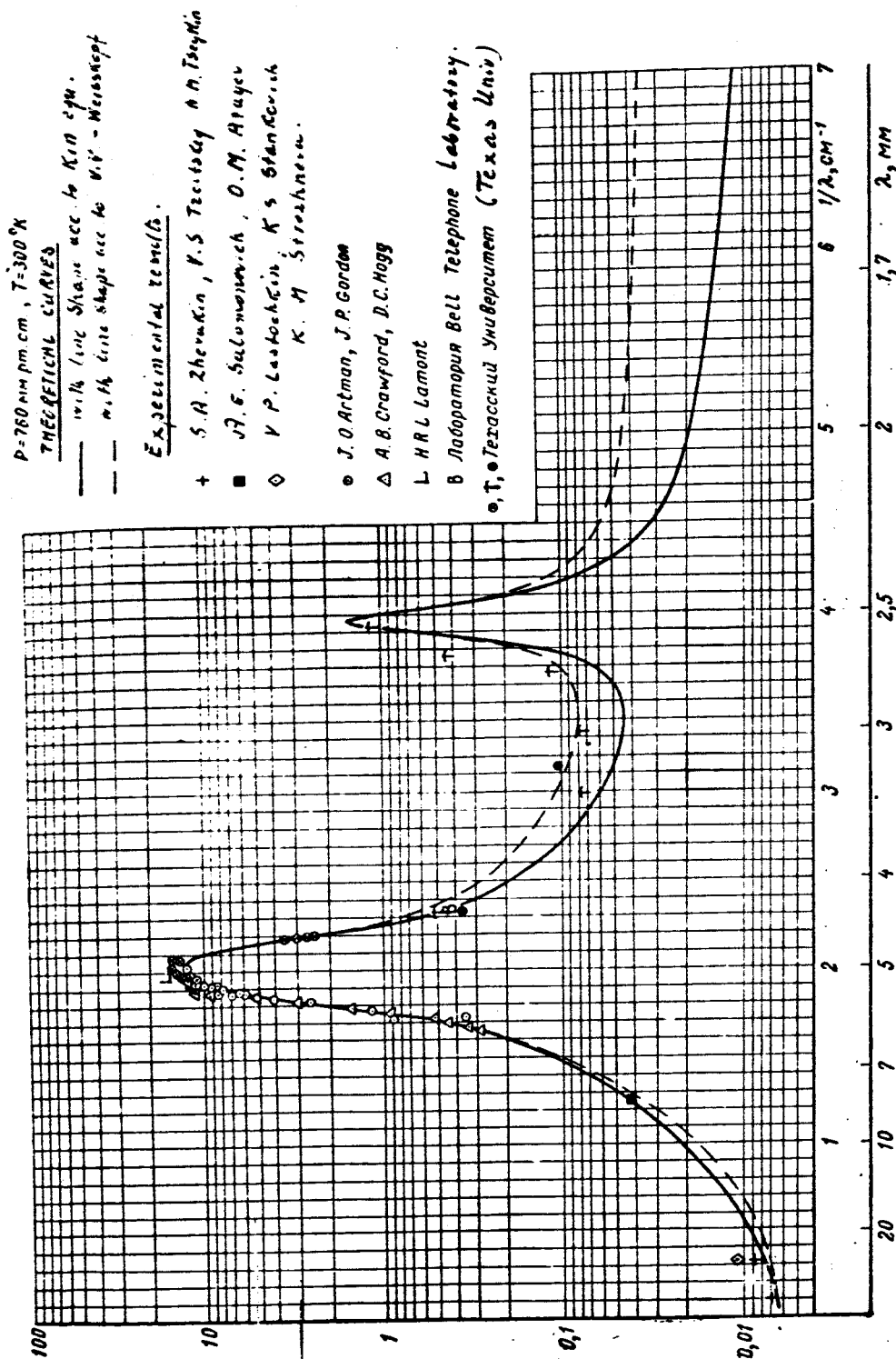


Fig. 2. - Comparison of the computed absorption factors with the line shape calculated by the kinetic equation & after Van Vleck-Weisskopf, with the experimental results of the works [5, 16, 21, 23, 50, 57-59]. It was assumed for both theoretical curves  $\Gamma = 2.064 \text{ mc/mm Hg}$ . The experimental points are either disposed at centers or intersections of respective signs.

It may be seen from Fig. 2 that the absorption factors of  $O_2$  computed with different shapes of spectral lines, differ little among themselves at  $\lambda > 2.3 \text{ mm}$  (cf. with the corresponding calculations for water vapor [1]). As a consequence of that, the experimental results of [12] in the frequencies  $\nu = 58-62 \text{ cps}$  ( $1/\lambda = 1.93-2.07 \text{ cm}^{-1}$ ) and in the region  $\nu \approx 65 \text{ cps}$  satisfy to an identical degree the absorption factors computed in this work and in [12], though at description in the latter of the absorption spectrum of  $O_2$ , a series of inaccuracies had been admitted (see above). The discrepancy between the computed (solid line) and the measured absorption in the region  $\lambda \approx 3 \text{ mm}$ , is possibly the result of incorrect accounting of the nonresonance absorption. The results of computations in the regions  $\lambda < 2.4 \text{ mm}$  and  $\lambda \geq 3 \text{ cm}$  are unreliable for the same reason. In particular, the experimental results of [54] in  $\lambda \approx 2.18$  and  $1.33 \text{ mm}$  exceed the computed data by almost one order\*. In wavelengths  $\lambda < 2 \text{ mm}$  the absorption in the atmosphere in standard conditions is determined by the rotational spectrum of water vapors [1-3]. The aggregate absorption factor of the atmosphere in centimeter and microwaves is represented in Fig. 4 of the work [3].

3. In [27], the equivalent path length of radiowaves in oxygen (H) for the exponential model of the atmosphere and in absorption minima was found to be  $5.3 \text{ km}$ \*\*. In [29-31] the values  $H \approx 9-11 \text{ km}$  were utilized, and in [11] the value  $H = 1.516 \text{ km}$  was used, while in [32], it is asserted that  $H = 4 \text{ km}$ . The calculations of the equivalent path length were effected by us according to formula

$$H = \int_0^{\infty} \gamma(z) dz / \gamma(0) \quad (5)$$

for a polytropic model of the atmosphere, as in [28]:

$$\left. \begin{aligned} P &= P_0 \left( \frac{T_0 - \kappa z}{T_0} \right)^{g/R\kappa} \\ T &= T_0 - \kappa z \end{aligned} \right\} z \leq 11 \text{ km},$$

$$\left. \begin{aligned} P &= P_{11} e^{-\beta(z-z_0)} \\ T &= T_{11} \end{aligned} \right\} 11 \text{ km} < z < \infty,$$

\* For more details on the results of [54], see [39].

\*\* The revision of the results of [27], undertaken in [28], is based on the erroneous opinion of immaterialness of contribution from the upper layers of the atmosphere ( $z > 11 \text{ km}$ ) to the quantity H.

Dependence of the Equivalent Path Length of Radiowaves in Oxygen on Frequency  
( Z E N I T H )

$\nu, \text{MHz}$	40	44	48	50	51	51,5	52	53	53,5	54	54,5	55	55,5	56	56,5	57	57,5	58
$H, \text{km}$	5,22	5,20	5,17	5,14	5,11	5,09	5,07	5,15	5,77	6,17	6,57	6,99	7,52	8,75	9,64	10,7	9,29	
$\nu, \text{GHz}$	58,5	59	59,5	60	60,5	61	61,5	62	62,5	63	63,5	64	64,5	65	65,5	66	66,5	67
$H, \text{km}$	13,7	10,5	12,2	9,55	14,6	10,4	9,08	9,73	18,3	21,0	9,02	7,62	6,84	6,31	5,90	6,50	5,11	5,08
$\nu, \text{THz}$	67,5	68	68,5	69	69,5	70	72	74	76	80	86	92	96	100				
$H, \text{km}$	5,07	5,09	5,11	5,12	5,14	5,15	5,18	5,19	5,21	5,22	5,24	5,26	5,29	5,23				

$\kappa = |dT/dz| = 6,5 \text{ deg/km}$ ,  $\delta = mg/kT_{11} = 0,151 \text{ km}^{-1}$   
 at mean molecular mass  $m = 0,151 \text{ km}^{-1}$ ,  $g$  is the gravitation acceleration,  $R$  - is a gas constant,  $P_{11}$  and  $T_{11}$  are the pressure and temperature at the height  $z_0 = 11 \text{ km}$ , respectively equal to  $181,6 \text{ mm Hg}$  and  $228,5^\circ \text{K}$ ,  $P_0$  and  $T_0$  are the pressure and temperature at sea level. The results of computation are compiled in the adjacent Table. They corroborated the values of  $H = 5,1 - 5,3 \text{ km}$  outside the resonance. At the same time, a dependence of  $\gamma_{nr} \sim P^2$  was taken, while the numerical integration of the resonance part of absorption in (4) was materialized on a BESM-II computer by the Simpson method. In the resonance region  $\nu \sim 56 - 64 \text{ cps}$ , the quantity  $H$  depends essentially on the frequency and can take values from  $\sim 8$  to  $21 \text{ km}$ . It has just as high a value ( $\sim 11 \text{ km}$ ) near  $\nu_{1-} \simeq 118,7 \text{ cps}$  too. We assumed in the course of computations, that the quantity  $(\alpha_{K+})_{av}$  rises linearly from  $1,17$  to  $1,95 \text{ Mc/mm.Hg}$  within the range of  $P$  variation from  $270$  to  $20 \text{ mm.Hg}$ . Such approximation of the dependence  $\Delta\nu(P)$ , is apparently no worse than (2), though it can not pretend to constitute a precise description of the above dependence. Incidentally, at other intelligent approximations of the correlation  $\Delta\nu(P)$ , including the expression (2), the difference in the respective values of  $H$  does not exceed  $\sim 5\%$ .

If we admit, that the dependence of the nonresonance absorption on pressure away from the resonance is described by the correlation  $\gamma_{nr} \sim P^2$ , as estimated above, the value of  $H$  in the regions where the nonresonance absorption is substantial (cm waves and waves  $\lambda < 2,3 \text{ mm}$ )

will result near 4 km [14]. Estimates, made in [55], show a certain dependence of the equivalent path length in oxygen on the time of the year.

Note, that in certain cases, at frequencies of the order of decimal fractions of giga-cps, the ionosphere absorption  $\Gamma$  can render the interpretation of measurements of vertical absorption in the atmosphere more complex, but for the median band of the European SSSR this correction is small. Thus, in winter, we usually have for Gor'kiy at noon  $\Gamma/\gamma H \sim 6\%$  at  $\lambda \simeq 50$  cm (we used for  $\Gamma$  the value obtained from data of [56], using the correlation  $\Gamma \sim \nu^{-2}$ ).

### CONCLUSIONS

1. By the strength of the characteristic of oxygen absorption spectrum, the divergence of absorption factors, computed with a line shape according to the kinetic equation, and with the erroneous shape of the Van-Vleck-Weisskopf line, is not too great in wavelengths  $\lambda > 2.3$  mm. This divergence is most substantial in the region  $\lambda \simeq 3$  mm (by  $\sim 1.8$  times).

2. At standard atmospheric conditions the absorption spectrum of  $O_2$  in the  $\lambda \simeq 4.1 - 6.7$  mm and  $\lambda \simeq 2.38 - 2.63$  mm bands can be quite satisfactorily described utilizing the spectral line shape from the solution of the kinetic equation and assuming the lines' half-widths to be  $\Delta\nu_{K \pm} = 0.81 \text{ giga-cps}$  ( $K \neq 1$ ) and  $\Delta\nu_1 = 1.43 \text{ giga-cps}$  (see Figs 1 and 2).

3. The equivalent path length of radiowaves in the atmosphere oxygen (zenith) outside the resonance depends little on frequency and is equal to 5.1 - 5.3 km for the case of polytropic atmosphere, which coincides with the earlier found characteristic length of oxygen absorption for the exponential model of the atmosphere [27]. In the resonance  $\nu \simeq 56 - 64$  giga-cps and the equivalent path length depends essentially on frequency being susceptible to attain a magnitude ranging from 8 to 21 km.

4. The unsolved problems of the theory of microwave absorption spectrum of  $O_2$  are those about the nonresonance absorption (quantitative aspect) and the dependences of  $O_2$  spectral lines' half-widths on pressure.

In conclusion, we wish to extend our thanks to L. A. Rakova and M. B. Flaksman for carrying out computer BESM- II operations.

\*\*\*\*\* THE END \*\*\*\*\*

# R E F E R E N C E S

1. S. A. ZHEVAKIN, A. P. NADMOV. Izv. vuzov MVSSO SSSR (Radiofizika), 6, 4, 674, 1963.
2. S. A. ZHEVAKIN, A. P. NAUMOV. Geomagnetizm i aeronomiya, 3, 4, 666, 1963.
3. S. A. ZHEVAKIN, A. P. NAUMOV. Radiotekhnika i elektronika, 9, 8, 1327, 1964.
4. J. H. VAN VLECK. Phys. Rev., 71, 7, 413, 1947.
5. A. B. CRAWFORD, D. C. HOGG. Bell System Techn. J., 35, 4, 907, 1956.
6. B. R. BEAN, R. ABBOTT. Geofis. pura e appl., 37, 2, 127, 1957.
7. M. L. MEEKS. J. Geophys. Res., 66, 11, 3749, 1961.
8. M. L. MEEKS, A. E. LILLEY. J. Geophys. Res. 68, 6, 1683, 1963.
9. A. W. STRAITON, C. W. TOLBERT. Proc. I. R. E., 48, 5, 898, 1960; Correction, Proc. I. R. E., 49, 1, 220, 1961.
10. E. S. ROSENBLUM. Microwave J., 4, 3, 91, 1961.
11. K. RAWER. J. Res. Nat. Bur. Standards, 66, 4, 375, 1962.
12. C. W. TOLBERT, A. W. STRAITON. Proc. I. E. E. E., 51, 12, 1754, 1963.
13. V. P. LASTOCHKIN, K. S. STANKEVICH. Izv. vuzov MVSSO SSSR (Radiofizika), 6, 6, 1098, 1963.
14. K. S. STANKEVICH. Izv. vuzov MVSSO SSSR (Radiofizika), 8, 1, 98, 1965.
15. F. FURSENBERG. Z. Astrophys., 49, 1, 42, 1960.
16. H. R. L. LAMONT. Phys. Rev., 74, 3, 353, 1948.
17. M. W. P. STRANDBERG, C. Y. MENG, J. G. INGERSOLL. Phys. Rev., 75, 10, 1524, 1949.
18. J. H. BURKHALTER, R. S. ANDERSON, W. V. SMITH, W. GORDY. Phys. Rev., 79, 5, 651, 1950.
19. R. S. ANDERSON, W. V. SMITH, W. GORDY. Phys. Rev., 82, 2, 264, 1952; 87, 4, 561, 1952.
20. B. V. GOKHALE, M. W. P. STRANDBERG. Phys. Rev., 84, 4, 844, 1951.

21. J. O. ARTMAN, J. P. GORDON. Phys. Rev., 96, 5, 1237, 1954.
22. C. W. TOLBERT, A. W. STRAITON. IRE Trans. Antennas and Propagat., AP-5, 2, 239, 1957.
23. C. W. TOLBERT, A. W. STRAITON. IRE Wescon Convent. Rec., 3, pt. 1, 56, 1959.
24. R. M. HILL, W. GORDY. Phys. Rev., 93, 5, 1019, 1954.
25. R. M. ZIMMERER, M. MIZUSHIMA. Phys. Rev., 121, 1, 152, 1961.
26. R. S. ANDERSON, C. M. JOHNSON, W. GORDY. Phys. Rev., 83, 5, 1061, 1951.
27. S. A. ZHEVAKIN, V. S. TROITSKIY. Radiotekhnika i elektronika, 4, 1, 21, 1959.
28. S. S. GREMYACHENSKIY. Vestn. Leningr. un-ta, Ser. fiz. i khimii, 10, 2, 69, 1962.
29. G. R. MARNER. Proc. I. R. E., 43, 3, 369, 1955.
30. R. N. WHITEHURST, J. COPELAND, F. H. MITCHELL. J. Appl. Phys, 28, 3, 295, 1957.
31. J. AARONS, W. R. BARRON, J. P. CASTELLI. Proc. I. R. E., 46, 1, 325, 1958.
32. Influence of the non-ionized regions of the atmosphere on the propagation of waves, Report Drafting Committee on the X-th Plenary Assembly C. C. I. R., Geneva, 7 February 1963.
33. M. STRENDBERG. Radiospektroskopiya, II, 1965.
34. M. TINKHAM, M. W. P. STRANDBERG. Phys. Rev., 99, 2, 537, 1955.
35. M. TINKHAM, M. W. P. STRANDBERG. Phys. Rev., 97, 4, 937, 1955.
36. W. KAHAN. Nature, 195, 4836, 30, 1962.
37. L. F. STAFFORD, C. W. TOLBERT. J. Geophys. Res., 68, 11, 3431, 1963.
38. M. R. SULLIVAN. Atmospheric absorption of radio signals at frequencies of 58 to 62 Kmc, M. S. thesis, University of Texas, Austin, January 1963.
39. A. P. NAUMOV. Izv. vuzov MVSSO SSSR (Radiofizika), 8, 3, 1965.
40. J. H. VAN VLECK, V. F. WEISSKOPF. Rev. Mod. Phys., 17, 2-3, 227, 1945.

41. E. P. GROSS. Phys. Rev., 97, 2, 395, 1955.
  42. S. A. ZHEVAKIN, G. M. STRELKOV. O forme spektral'noy linii, obuslovlennoy soudareniyami (On the spectral line shape conditioned by collisions), Dokl. na XV Vsesoyuznom soveshchanii po spektroskopii, Minsk, 5 - 11 iyulya, 1963, Tezisy dokladov, Izd. A. N. BSSR str. 63, 1963.
  43. L. GOLATRY, A. ROBERT. Planet Space Sci., 11, 10, 1139, 1963.
  44. A. ROBERT. L'Echo des Recherches, 43, 3, 1963.
  45. A. G. BARRETT. Microwave spectral lines as probes of planetary atmospheres, Memoires de la Societe Royale des Sciences de Liege, 7, fasc. unique, Liege Universite, 1963.
  46. M. MIZUSHIMA, R. HILL. Phys. Rev., 93, 4, 745, 1954.
  47. A. A. MARYOTT, G. BIRNBAUM. Phys. Rev., 99, 6, 1886, 1955; J. Chem. Phys., 32, 3, 686, 1960.
  48. A. BATTAGLIA, A. COZZINI, M. IANNUZZI. Arch. sci. 14, fasc. spec., 93, 1961.
  49. M. IANNUZZI, N. MINNAJA. Nuovo cimento, 30, 4, 997, 1963.
  50. C. W. TOLBERT, A. W. STRAITON, A. WALKER. U. S. Govt. Res. Repts, 37, 15, 6, 1962.
  51. J. M. HOLLANDER, I. PERLMAN, G. T. SEABORG. Rev. Mod. Phys., 25, 2, 469, 1953.
  52. S. L. MILLER, A. JAVAN, C. H. TOWNES. Phys. Rev., 82, 3, 454, 1951; 83, 1, 209.
  53. S. L. MILLER, C. H. TOWNES. Phys. Rev., 90, 4, 537, 1953.
  54. M. COHN, F. L. WENTWORTH, J. C. WILTSE. Proc. I. E. E. E., 51, 9, 1227, 1963.
  55. V. V. KUZOVLEV, K. S. STANKEVICH. Izv. vuzov MVSSO SSSR (Radiofizika), 3, 6, 957, 1960.
  56. E. A. BENEDIKTOV, YU. S. KOROBKOV, N. A. MITYAKOV, V. O. RAPPOPORT, L. N. KHODALEVA. Izv. vuzov MVSSO SSSR (Radiofizika), 3, 6, 957, 1960.
  57. A. E. SALOMONOVICH, A. M. ATAYEV. Izv. vuzov MVSSO SSSR (Radiofizika), 3, 4, 606, 1960.
  58. S. A. ZHEVAKIN, V. S. TROITSKIY, N. M. TSEYTLIN. Izv. vuzov MVSSO SSSR (Radiofizika), 1, 2, 19, 1958.
  59. V. P. IASTOCHKIN, K. S. STANKEVICH, K. M. STREZHNEVA. Izv. vuzov MVSSO SSSR (Radiofizika), 7, 5, 984, 1964.
-



DISTRIBUTIONGODDARD SFC

600 TOWNSEND  
STROUD  
610 MEREDITH  
SEDDON  
611 McDONALD  
ABRAHAM  
BOLDT  
612 HEPPNER  
NESS  
613 KUPPERIAN [3]  
614 LINDSAY  
WHITE  
615 BOURDEAU  
BAUER  
AIKIN  
STONE  
GOLDBERG  
JACKSON  
640 HESS [3]  
HARRIS  
MAEDA  
643 SQUIRES  
660 GI for SS [5]  
252 LIBRARY [3]  
256 FREAS

NASA HQS

SS NEWELL, CLARK  
SG NAUGLE  
SCHARDT  
SCHMERLING  
DUBIN  
SL LIDDEL  
GAUGLER  
FELLOWS  
HIPSHER  
HOROWITZ  
SM FOSTER  
ALLENBY  
GILL  
BADGLEY  
RR KURZWEG  
RRP GESSOW  
RRA WILSON  
RTR NEILL  
ATSS SCHWIND [4]  
ROBBINS  
WX SWEET

OTHER CENTERS

AMES R.C.  
SONETT [5]  
LIBRARY [3]  
LANGLEY R.C.  
160 ADAMSON  
HESS  
213 KATZOFF  
231 O'SULLIVAN  
235 SEATON  
185 WEATHERWAX [2]  
JPL  
SNYDER [3]  
UCLA  
COLEMAN  
U. MICH.  
ARNOLD  
MIT  
BARRETT  
UC BERKELEY  
WILCOX  
EDGERTON G.G.  
L.H. LEONARD

CONTRACT No. NAS-5-3760  
Consultants & Designers, Inc.  
Arlington, Virginia

Translated by ANDRE L. BRICHANT  
on 5 - 9 July 1965